Title: Estimation of Salt and Fresh Water Transports in the Bay of Bengal

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Award Number: N00014-11-1-0700

LONG-TERM GOALS

In the Indian Ocean, on annual time scales, there is a considerable exchange of salt and freshwater transports from Bay of Bengal (BoB) to the Arabian Sea (AS) and vice versa, and the paths of the high/low salinity waters are still speculative only. An important view of the pathways is the advection of low salinity waters from the BoB to the Southeastern Arabian Sea *via* the coastal Kelvin waves. The goal of this project is (i) to determine the propagation in the variability of coastally trapped Kelvin waves in the northern Indian Ocean, to establish pathways of fresh and salt water transports through the BoB to the AS, and to understand the impact of salinity on tropical cyclogenesis in the BoB; (ii) Pathways of fresh and salt water transport are investigated in the BoB and throughout the Indian Ocean.

OBJECTIVES

- Observe coastal Kelvin wave propagation across the equatorial Indian Ocean and along the perimeter of the Bay of Bengal
- Examine possible pathways of fresh and salt transports in the Bay of Bengal and Arabian Sea.

APPROACH

Understanding the coastal Kelvin wave propagation and the associated coastal circulation in the BoB is important because of its effect on energy propagation and mass transport around the basin. Also, coastal Kelvin waves in the BoB generate westward-propagating Rossby waves that also transport mass and energy. Both Kelvin waves and Rossby waves impact surface circulation and currents throughout the Indian Ocean. In this project we looked at observations using satellite altimetry (Topex/Poseidon and Jason-1&2) data, model simulations of HYbrid Coordinate Ocean Model (HYCOM), Simple Ocean Data Assimilation (SODA) reanalysis, and Aquarius salinity. In this study we will used the global HYbrid Coordinate Ocean Model (HYCOM) with a horizontal resolution of 1/12° (~7 km at mid-latitudes) and 32 hybrid layers in the vertical.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **Estimation of Salt and Fresh Water Transports in the Bay of Bengal**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of South Carolina,Department of Earth and Ocean Sciences,Columbia,SC,29208**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

This is only one year funded project started on 4 May, 2011 and ending on 30 September 2012. We have requested 4 months no-cost extension to finish this project. During this project we have obtained the HYCOM simulations during 2003-present and estimated the seasonal variability of salt transport in the Indian Ocean. Mechanisms and physical parameters that control the salinity budget are examined in the BoB. We have published two journal articles from this project and one more article in preparation.

RESULTS

(1) Seasonal variability of salt transport during the Indian Ocean monsoons

The seasonal variability of salt transport in the Indian Ocean is investigated using the high 1/12° global HYbrid Coordinate Ocean Model (HYCOM). Mechanisms and physical parameters that control the salinity budget are examined. Results show the influence of freshwater forcing and zonal advection as the dominant mechanisms of Sea Surface Salinity (SSS) variability. Precipitation is highest in the eastern Bay of Bengal (BoB) where it shows seasonal variation and in the south equatorial eastern Indian Ocean (EIO) where it was consistently high year round. These patterns result in significant seasonal variation in the SSS in the BoB and almost no variation in the EIO (Figure 1). Zonal SSS transport was higher than meridional SSS transport with the strongest seasonality observed along the Sri Lankan region. Results of depth integrated transport shows northward salt transport in the bottom layers and a southward salt transport in the surface layers. The 4-year mean net flux of depth-integrated salt transport was southward (-154.8×10^6 kg/s to -552.4×10^6 kg/s) at all latitudes except at 20°N (Figure 2) where it was northward (396×10^6 kg/s). Transport generally increases southward with the highest transports occurring in the south (10°S-35°S) and a maximum at 30°S (Figure 3). Analyses of meridional Ekman volume and salt transport show a predominantly southward transport, an indication of the strong influence of SW monsoonal winds. It is anticipated that this study will be useful in computing salt transport using satellite derived salinity data from the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) and NASA Aquarius salinity missions.

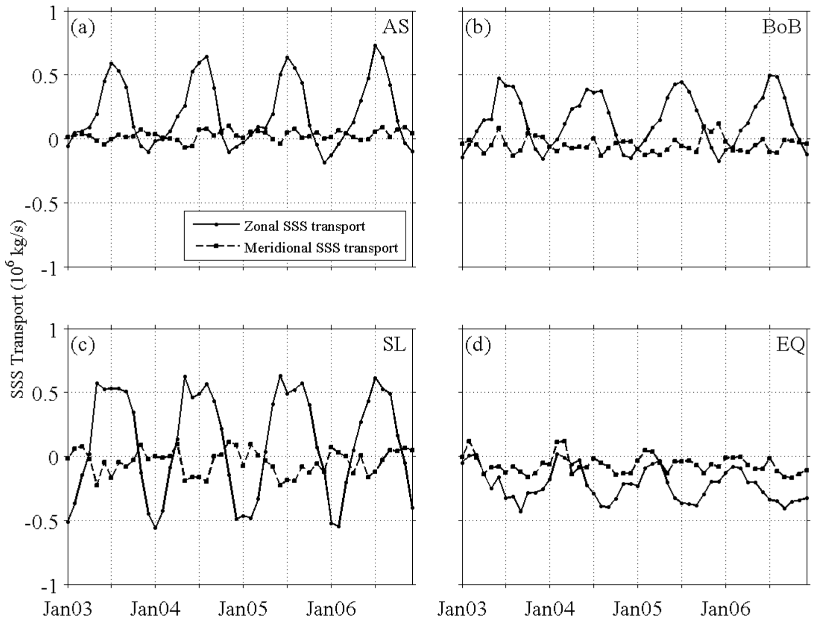

Figure 1. Seasonal variation of area-averaged zonal and meridional surface salinity transport for the Arabian Sea (AS), Bay of Bengal (BoB), Sri Lanka (SL) and Equatorial (EQ) regions.

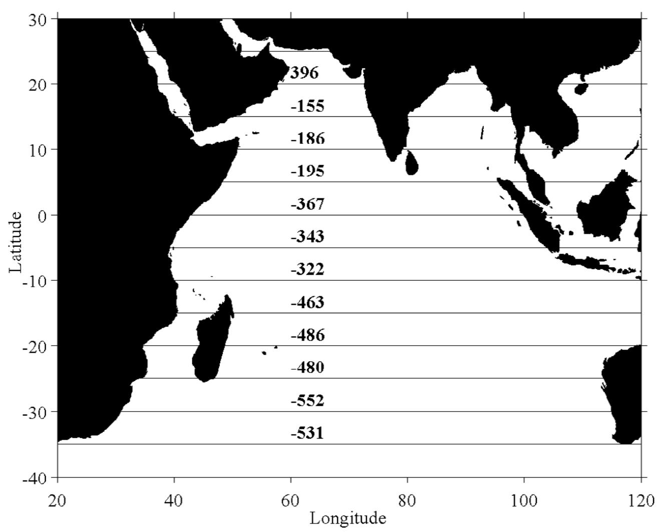

Figure 2. Annual mean depth integrated net meridional salt transport (× 10^6 kg/s) for each 5° latitude belt in the Indian Ocean.

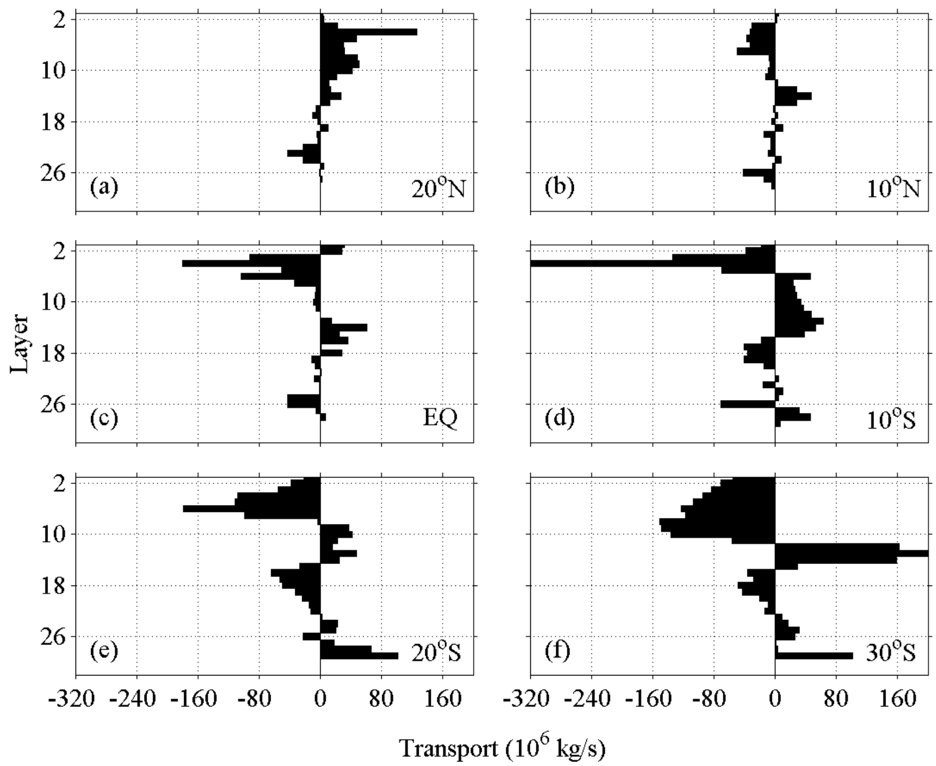

Figure 3. Depth integrated meridional salt transport in each layer integrated along latitudinal sections in the Indian Ocean computed from 4-year mean HYCOM simulations. Positive transport is to the north.

(*2) Altimetric observations and HYCOM Model simulations of coastal Kelvin waves in the Bay of Bengal*

In this paper, Kelvin waves are observed as they propagate annually throughout the BoB (Figures 4 and 5). The variability in the propagation of the upwelling coastal Kelvin waves during the winter monsoon (January-March) and summer monsoon (July-September) and the downwelling coastal Kelvin waves during the summer monsoon transition (April–June) and winter monsoon transition (October–December) are investigated and compared throughout the time series measured, using altimetry data, Hybrid Coordinate Ocean Model (HYCOM) simulations and Simple Ocean Data Assimilation (SODA) reanalysis.

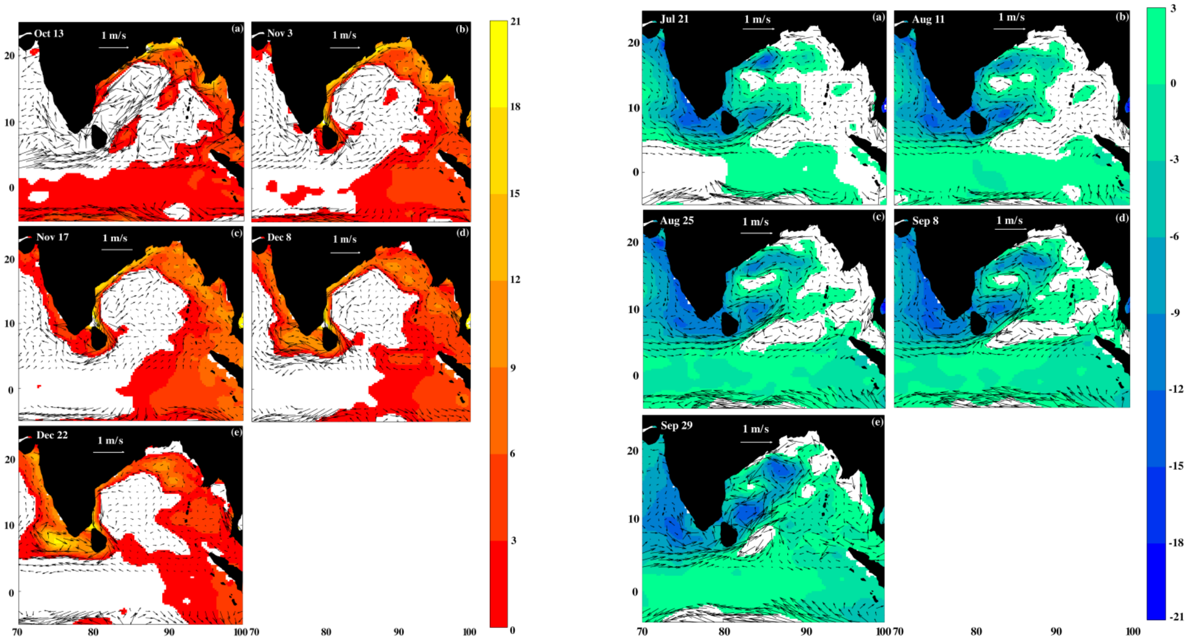

Figure 4. 13 year weekly average sea surface height anomaly (SSHA) data (cm) from altimetry in the Indian Ocean, displayed at 2-3 week intervals from October – December (left) and July-September (right). Only positive (negative) values of SSHA are displayed to show the propagation of the second downwelling (upwelling) Kelvin wave. Overlaid are the weekly averaged geostrophic sea surface current vectors calculated using U and V from altimetry data. Geostrophic currents from 3°N to 3° S were removed

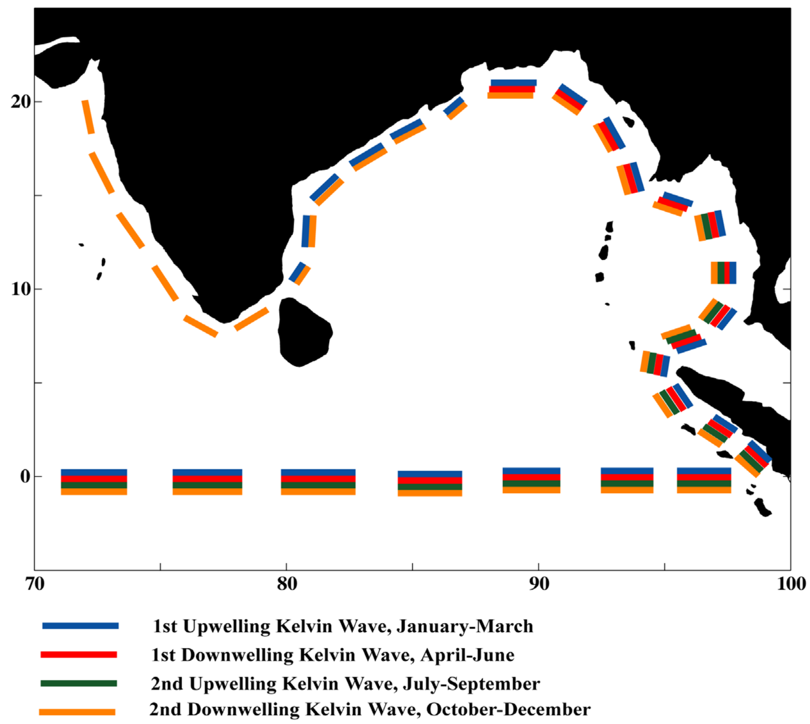

Figure 5: Schematic diagram of the observed propagation of the upwelling (January-March in blue, July-September in green) and downwelling (April – June in red, October – December in orange) Kelvin wave phases. Dissipation of wave signals is seen along the Mynamar coast, east coast of India and west coast of India. Only the 2nd downwelling Kelvin wave propagates up to the northern extent of the west coast of India.

At 0°N, 77°E, zonal velocity anomalies (U, Figure 6a) range from -0.16 m/s to +0.16 m/s. The westward (negative) zonal velocity in January, boreal winter season, is a manifestation of the first upwelling Kelvin wave, followed by the first downwelling (eastward, positive zonal velocity) in April/May, the second upwelling Kelvin wave in August-September. The second downwelling Kelvin wave first appears at the thermocline during September-October and then progresses towards the surface by November-December and is stronger than the first downwelling Kelvin wave. This higher strength in the second downwelling Kelvin wave has an impact on its persistent propagation from the equatorial Indian Ocean to the west coast of India, as has been noticed in the previous paragraphs.

Similarly, the alongshore current velocity anomalies at 2°N, 94°E (off northern Sumatra, Figure 6b) also shows the first and second downwelling Kelvin waves associated with the northward (positive) alongshore velocity anomaly during April-May and October-December at thermocline depths. The alongshore southward velocity associated with the first and second upwelling Kelvin waves is weaker and limited to shallow layer only. Thus, the alongshore velocity off the northern Sumatra has a close relation to the extent of the progressive propagation of the Kelvin waves around the coastal periphery of the Bay of Bengal. These coastal Kelvin waves have a propagating horizontal speed of ~2.5 m/s and a vertical speed of ~1.2 m/day.

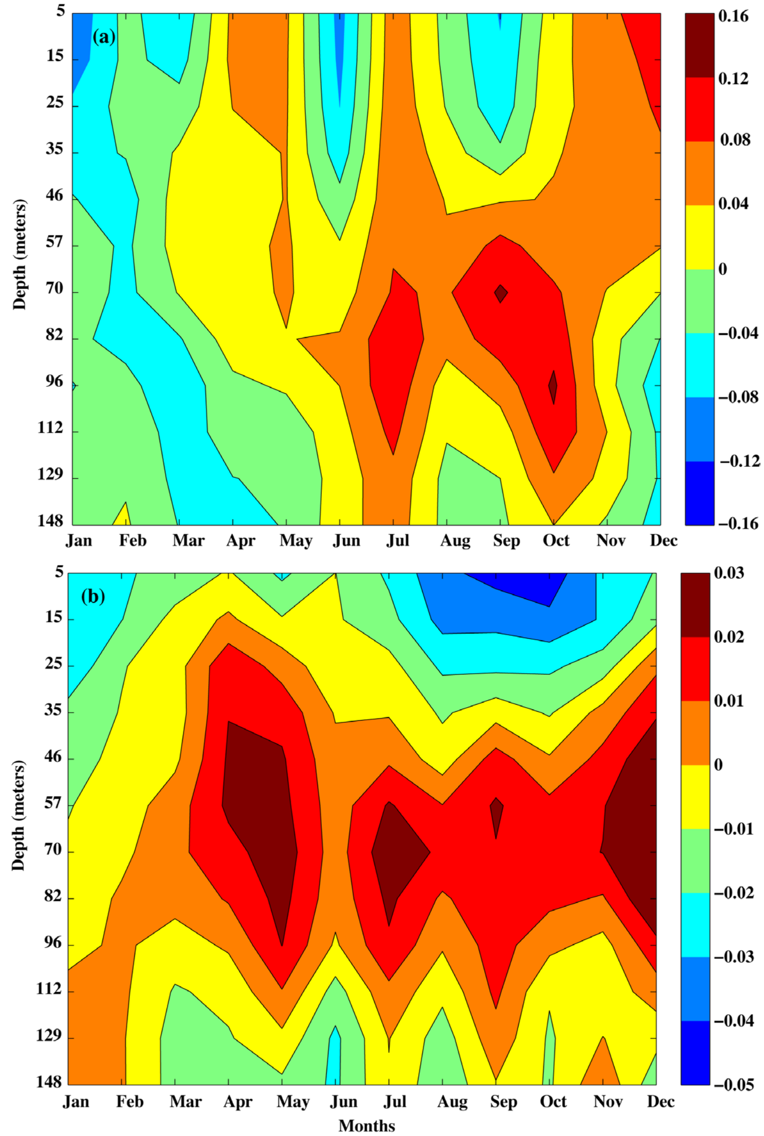

Figure 6. Time series of (a) zonal (U) current velocity anomalies (m/s) averaged from SODA reanalysis at 0°N, 77°E (south of India on equator) and (b) alongshore current velocity (V) anomalies (m/s) averaged from SODA reanalysis at 2°N, 94°E (near Sumatra coast) over the period from 1993-2006. The top 12 layers of SODA reanalysis correspond to a depth of about 148 m.

IMPACT/APPLICATIONS

For Naval applications, understanding the stratification in the Bay of Bengal and in the Indian Ocean is relevant in the area of anti-submarine warfare. Salinity and temperature variations impact the spatial density field and the depth of the mixed layer, and the formation of the barrier layer. The barrier layer is defined as the extent of water column from the depth of mixed layer to the depth of the isothermal layer. The dynamics associated with the barrier layer formation are important for acoustic performance and its predictions. The regions like the Bay of Bengal where freshwater occupies the top layer, the sound velocity profile will change and there will be acoustic losses. Internal waves can be

generated due to the strong salinity stratification and the associated strong density stratification, and barrier layer formation occurs. Also, this investigation falls within ONR's quest to understand "environmental evolution, assimilation of data, and the limits of predictability by planning, fostering and encouraging scientific inquiry and technological development in the fields ranging from littoral geosciences to high latitude dynamics."

RELATED PROJECTS

None

PUBLICATIONS

- ***Refereed Publications***

1. Nyadjro, E.S., B. Subrahmanyam, and J.F. Shriver (2011). Seasonal Variability of Salt Transport during the Indian Ocean Monsoons, Journal of Geophysical Research, 116, doi:10.1029/2011JC006993.
2. Nienhaus, M.S., and **B. Subrahmanyam**, and V.S.N. Murty (2012). Altimetric Observations of Coastal Kelvin Waves in the Bay of Bengal, *OSTM/Jason-2 special issue, Marine Geodesy* (in press).

- ***Conference/Workshop presentations***

1. Grunseich, G., and B. Subrahmanyam (2011). Validation of SMOS salinity data and its applications to Indian Ocean climate events, *Oceans 2011 MTS/IEEE Kona*, Kona, HI. Sept. 17, 2011-Sept. 22, 2011 (*Oral Presentation*).
2. Nienhaus, M., and B. Subrahmanyam (2011). Role of costal Kelvin waves on the Bay of Bengal Circulation, Fall AGU meeting, San Francisco, 13-17 December, 2011 (*Oral Presentation*).
3. Nienhaus, M., and B. Subrahmanyam (2011). Altimetric Observations of Coastal Kelvin waves in the Bay of Bengal Circulation, Costal Altimetry meeting & NASA/OSTST meeting, San Diego, 10/16-10/20, 2011 (*Oral Presentation*).
4. Nyadjro, E.S., and B. Subrahmanyam, 2011. Variability of salt transport in the Indian Ocean. AGU *Fall Meeting*, San Francisco, 13-17 December, 2011(*Oral Presentation*).
5. Subrahmanyam, B. E.S. Nyadjro, and V.S.N. Murty (2011). Near Surface Salt Transport in the Indian Ocean using HYCOM, submitted for Oral Presenation in 2011 ASLO Aquatic Science Meeting, San Juan Puerto Rico, 13-18, Feb 2011. (*Oral Presentation*).

HONORS/AWARDS/PRIZES

(1) Ebenezer Nyadjro (Graduate student)

- Awarded 2012 Outstanding Dissertation Award.
- Awarded The National Academies/National Research Council (NRC)/ Research Associateship to work at NOAA/PMEL

- Awarded F. John Vernberg Best Publication Award
- Awarded USC Graduate Student Day oral presentation second prize.
- Awarded F. John Vernberg Outstanding Graduate Teaching award
- Selected as a participant in the Physical Oceanography Dissertation Symposium (PODS VII) held at Lihue, Kauai during October 7-11, 2012.

(2) Gary Grunseich (Graduate Student)

- Awarded Taber Award for Outstanding Masters Research in the Field of Geological Sciences